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Growth of Laser Initiated Damage in Fused Silica at 1053 nm

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ABSTRACT

The effective lifetime of a laser optic is limited by both laser-induced damage and the subsequent growth of laser initiated damage sites. We have measured the growth rate of laser-induced damage on polished fused silica surfaces in 10 torr of air at 1053 nm at 10 ns. The data shows exponential growth in the lateral size of the damage site with shot number above a threshold fluence. The size of the initial damage influences the threshold for growth. We will compare the growth rates for input and output surface damage. Possible reasons for the observed growth behavior are discussed.

Keywords: Laser damage, laser damage growth, laser damage growth threshold, UV fused silica.

1. INTRODUCTION

The lifetime of optics used in laser applications is limited both by laser-initiated damage and by the subsequent growth of the laser-initiated damage. Since a laser initiated damage site is typically only tens of microns in diameter, if it was stable on subsequent shots, the performance of the optic might be considered acceptable in many applications. If the laser initiated site is not stable and increases in size, the performance of the optic will degrade with the number of laser shots until it finally cannot be considered useful. Thus, it is the growth of laser-initiated damage, which generally dictates the lifetime, and consequently the true cost of optics for a laser application.

Unlike typical damage experiments, which are concerned with measurements of the damage threshold of fused silica, this work focuses on the growth of damage after laser initiation. The growth rate of laser-induced damage in UV grade fused silica has been measured at 1053 nm under a variety of conditions. Measurements of growth rate have been made in 2.5 and 10 torr of dry air, on sites initiated on bare surfaces. The influence of the initial starting size on growth rate has been considered. Since initiation of damage is more likely to occur on the exit surface of an optic, we have concentrated on growth of sites located on the exit surface of the optic. The significant finding in this work is that the growth rate of the lateral size with shot number shows exponential behavior when the damage is located on the exit surface of the optic. This is in contrast to the linear growth character of sites located on the input surface of the optic.

2. EXPERIMENTAL DETAILS

Laser damage initiation thresholds are typically measured with small beam laser systems where the beam profile is Gaussian and of diameter on the order of 1-mm. To make measurements of laser damage growth that are relevant to large beam areas as are found on the National Ignition Facility (NIF) and other high energy laser systems, it is necessary to use a beam with an area large relative to the initial damage size. At LLNL, a unique laser facility can provide a large area, 1053 nm beam along with a high rep rate. The laser is the SLAB laser system[1], a Nd: glass zig-zag slab amplifier, with SBS phase conjugation producing a near diffraction limited 1.053 μm output. This is the workhorse of the growth measurements. As used for these experiments it provides a 20 J, 1053 nm, 25 mm x 25 mm square beam, with a 10 to 12 nsec FWHM near Gaussian pulse, at a rep rate of 0.5-Hz. This rep rate is limited by data collection rate, as the laser system can be operated at 5 Hz.

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The key components of the layout for these experiments with the SLAB laser are shown in figure 1. The 1-micron beam is image relayed onto the experiment table where it is reduced from 2.5 cm x 2.5 cm to 1.7 cm by 1.7 cm and is spatially filtered before it is transported to the sample chamber. The sample is located in an image relay plane of the laser and the beam size on the part is nominally 5 mm x 5 mm. The laser is incident at 15º.

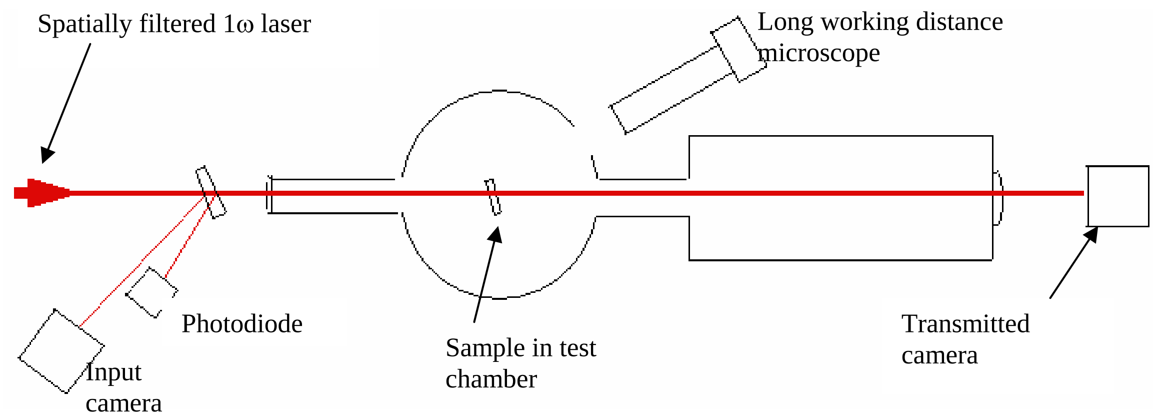
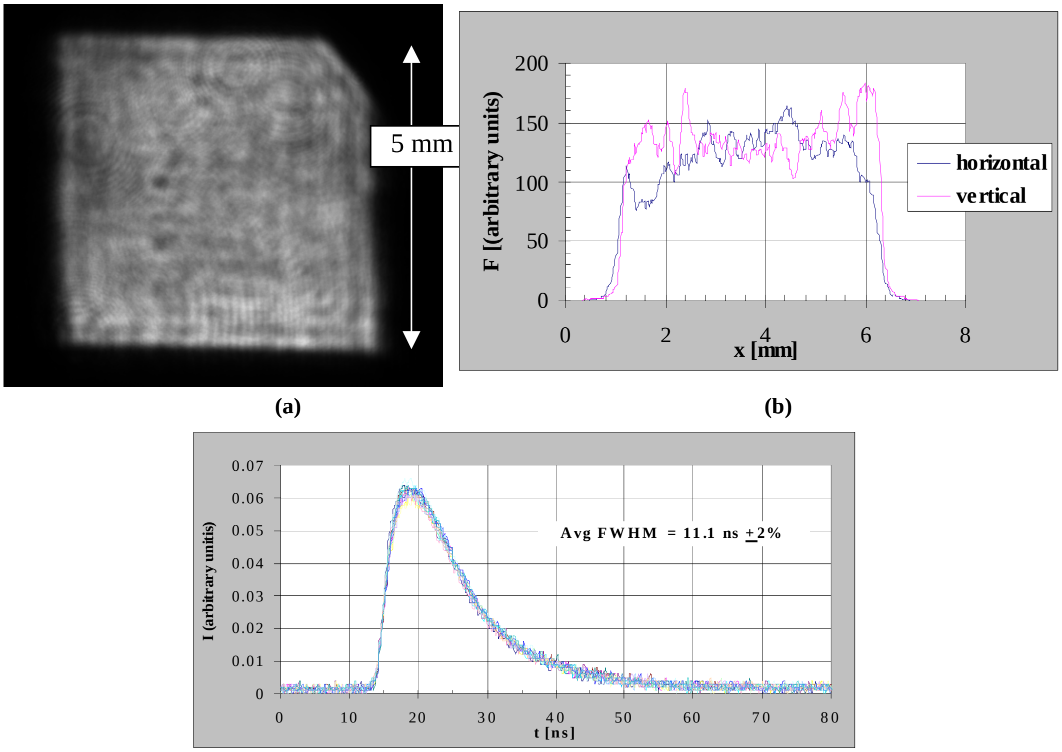


Figure 1. Layout of experiments.

The sample is housed in a stainless steel vacuum chamber, which is located in a class 100 area where samples up to 150 mm x 150 mm in size are handled during loading. For these tests, conducted in air at 2-10 torr, dry filtered high purity air is used to fill the chamber after it has first been pumped out to vacuum.

Laser beam measurements for the test beam on the part include measurement of the temporal pulse shape, energy and input & output beam near field intensity profiles. Diagnostics to measure the growth include a white light illuminated, long working distance microscope and CCD camera and scientific grade CCD camera viewing the transmitted light through the site. The workhorse for the growth measurements is a 16-bit scientific-grade CCD camera that samples the input beam incident on the part. It is calibrated both for energy and for magnification and is used to set and record the fluence on the sample for each shot. A typical near field image of the beam on the sample is shown in figure 2a. The calculated statistics for this beam is a contrast ratio of 17% over the central 80% of the beam area. Horizontal and vertical profiles through the beam center are shown in figure 2b. In practice, the camera viewing the beam transmitted through the sample is used to locate the starting damage and the input camera is used to set the local fluence in a 1-mm patch surrounding the site. The lateral growth of the damage site can be measured either from the transmitted camera or from the microscope. The temporal pulse width is approximately 11 ns; an overlay of 18 consecutive temporal waveforms are shown in figure 2c, where the average FWHM=11.1 ns ± 2%.

The samples are fused silica, UV grade Corning 7980, 2-inch round 1-cm thick and were super polished by SESO. Laser damage was initiated off-line at 351 nm with a single shot at a fluence level near 45 J/cm^2 with a 7.5 nsec FWHM Gaussian pulse. This high initiating fluence was chosen to produce repeatable damage spots in both size and morphology; even so there were variations in the site morphology. The lateral size and the number of individual pits in a site were cataloged; a typical initiated site is shown in figure 3. The sites typically contained multiple pits varying in individual sizes from 10 to 60 μm; some of these pits have a visible crack network associated with them and some pits are joined with adjacent pits.



(a) **(b)**

(c)

Figure 2. Typical 1ω beam image and spatial and temporal profiles.

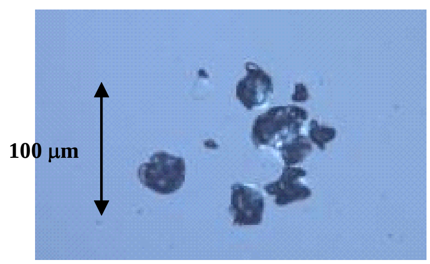


Figure 3. Micrograph of typical initiated site.

3. RESULTS

3.1 Growth of exit surface damage at fixed fluence.

The primary goal of this work is to obtain the growth rate of laser damage on the exit surface. The result of all data obtained under conditions where the site was illuminated with a fixed, single fluence during the entire growth sequence is considered in this section. For this data, the site is allowed to grow until the diameter reaches two or more millimeters. At least 50 shots at the working fluence are accumulated before reporting that a site does not grow. In some cases as many as 300 shots were accumulated before reporting a zero growth site.

After each laser shot, the lateral area of the damaged site was measured. The lateral diameter of the damage was calculated from the measured area by assuming a circular equivalent area. A typical growth plot with the effective diameter plotted vs. shot number is shown in figure 4. Also plotted on the graph is the average fluence surrounding the growing site. What we have measured on all sites showing growth, regardless of the starting morphology, is exponential growth of the lateral diameter with shot number. The data is fit to an exponential curve given by

$$D = D_0 e^{\alpha N} \tag{1}$$

where D is the effective lateral diameter of the damage, N is the shot number and α is the growth coefficient. The lateral growth spurts seen in the plots are typified by a few shots where crack growth seen on the perimeter is followed by apparent spallation of material with this cycle repeating itself. The exponential fit to the data in figure 4 is shown along with the R-squared value for this fit. All of the sites tested show comparable fits to the data.

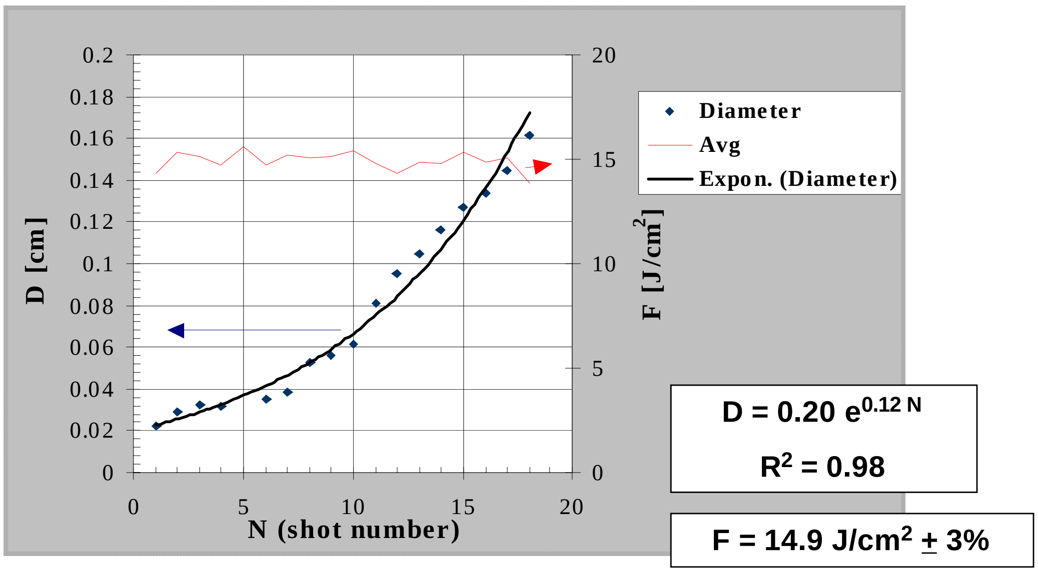


Figure 4. Typical lateral growth behavior showing exponential growth with shot number.

The exponential growth behavior plotted in figure 4 is obtained from the transmitted laser beam during the growth sequence. This growth behavior is shown in figure 5 for some of the shots.

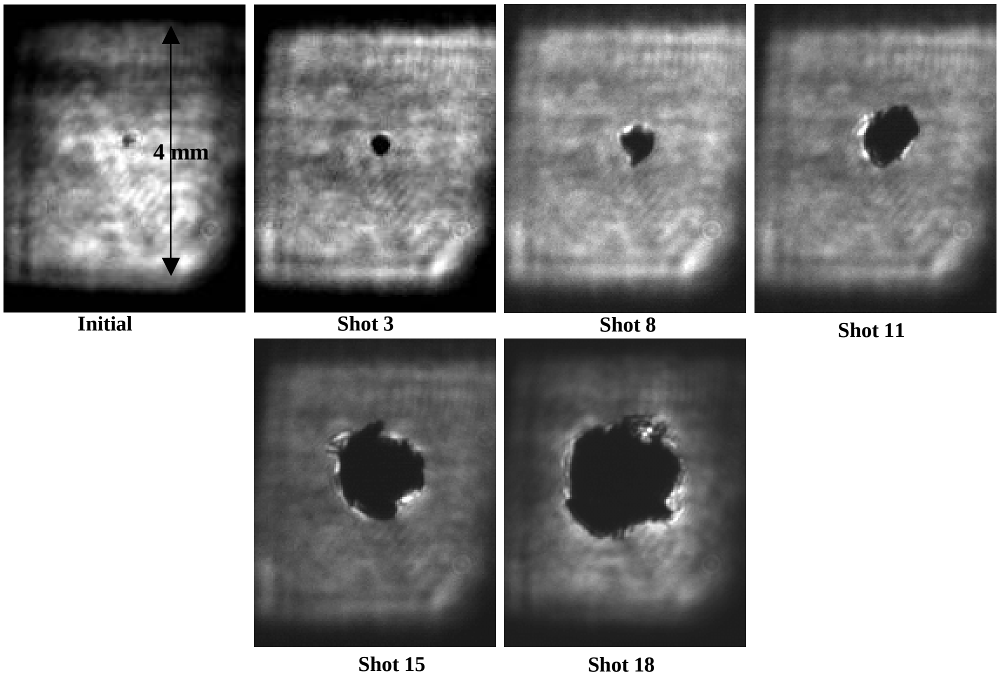


Figure 5. Transmitted camera images of growing damage site.

Plots of the growth coefficient vs. fluence for many sites shot at a fixed fluence show a threshold behavior for growth as can be seen in figure 6 where both the growth and no growth data are plotted. A linear fit to all the non-zero data is shown as the dark solid line. No growth was measured at 1ω for fluences less than 15 J/cm^2. There were sites that did not grow at fluences as high as 38 J/cm^2 but all sites shot at 40 J/cm^2 or greater did grow.

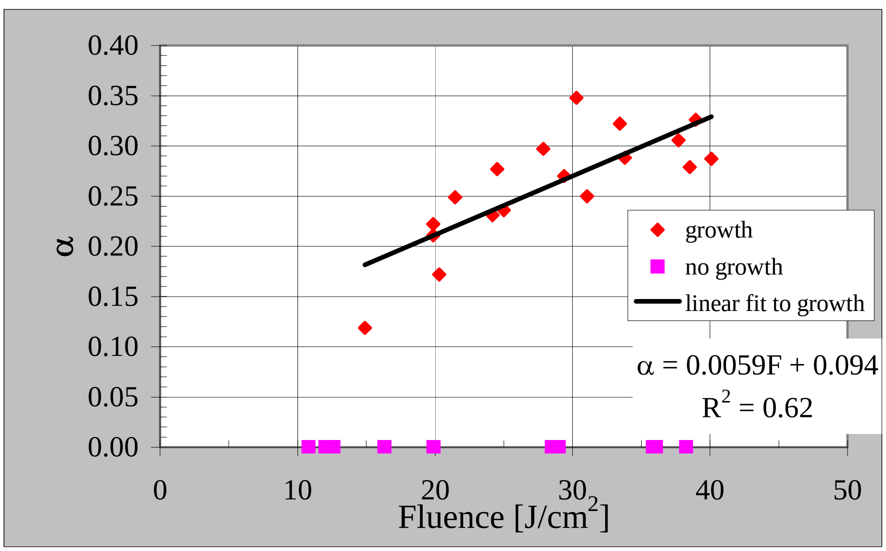


Figure 6. Plot of growth coefficients for 1ω vs. fluence.

We examined the initial micrographs to determine if the starting morphology could predict the site's potential for exponential growth at fluences greater than 15 J/cm^2. Some of the micrographs of the sites plotted in figure 6 are shown in figure 7. The two sites in figure 7a did not grow at ~30 J/cm^2 wheras the two sites seen in figure 7b did grow at ~30 J/cm^2. Though these sites and the others studied did suggest that heavily damaged sites grow more readily, the micrograph does not tell the whole story as is exemplified by figure 7c which did grow at ~15 J/cm^2 even though it looked most similar to a lightly damaged site.

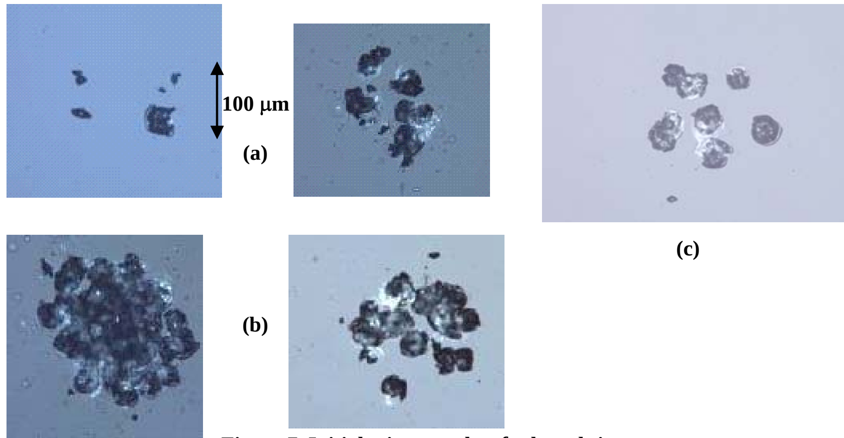


Figure 7. Initial micrographs of selected sites.

3.2 Growth of exit surface damage sites when fluence is ramped.

In an effort to establish a threshold for growth, we started shooting at low fluence, typically 12 J/cm^2, for 50 shots. If the site did not change, we increased the fluence and again observed for 50 shots; this cycle was repeated all the way to 40 J/cm^2 unless growth occurred. Figure 8 plots the fluence history and shows the starting micrograph for one such site. What we found using this technique was that two out of two sites did not grow after ramping all the way to 40 J/cm^2, whereas eight out of eight sites grew on the very first shot when immediately shot at 40 J/cm^2. Based on this observation, we concluded that this was not a viable technique to determine the threshold for growth. This limited data suggests that the threshold for growth might be increased by a conditioning sequence of shots.

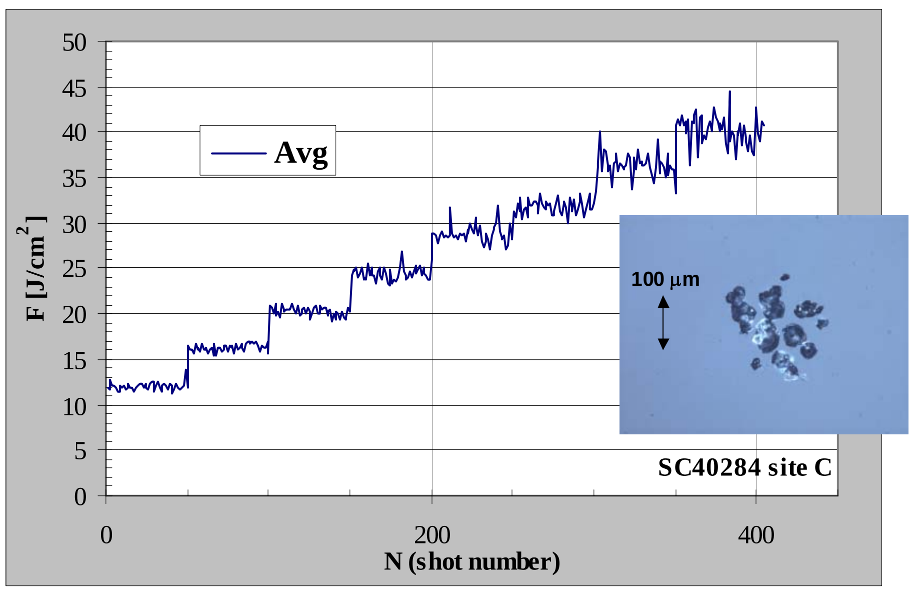


Figure 8. Ramped fluence shot history and micrograph.

3.3 Growth of exit surface damage when growth is triggered.

In order to determine if there is no growth at fluences less than 15 J/cm^2, we shot some sites at a high fluence for a single shot and then lowered the fluence for the second and subsequent shots. Figure 9 shows the data for one of these sites. The initial on-line micrograph and the micrograph taken after the single high fluence shot at 40 J/cm^2 shows that the site had started to grow both internally and externally, showing a small increase in diameter. In this case, the site did indeed continue growing at the reduced fluence of 10 J/cm^2, but at a significantly reduced rate than had been measured for growth at 40 J/cm^2. The growth data for all of the sites subjected to a high fluence shot followed by a lower fluence sequence of shots is shown in figure 10 along with the data obtained at a single fluence which was plotted in figure 6.

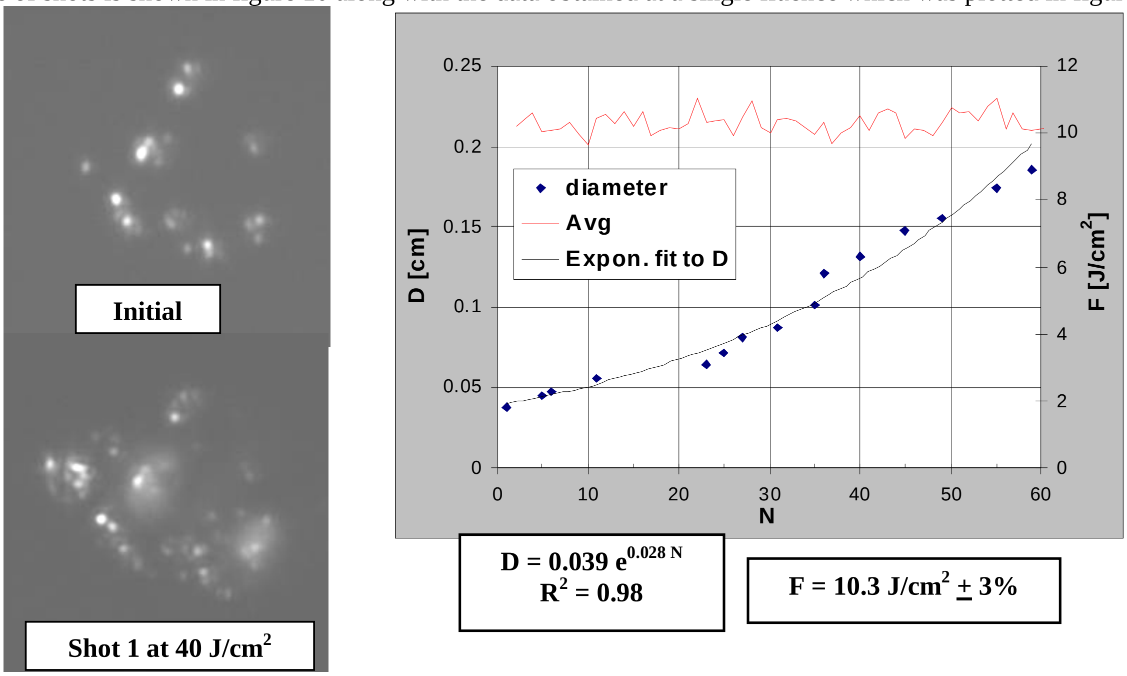


Figure 9. Triggered growth.

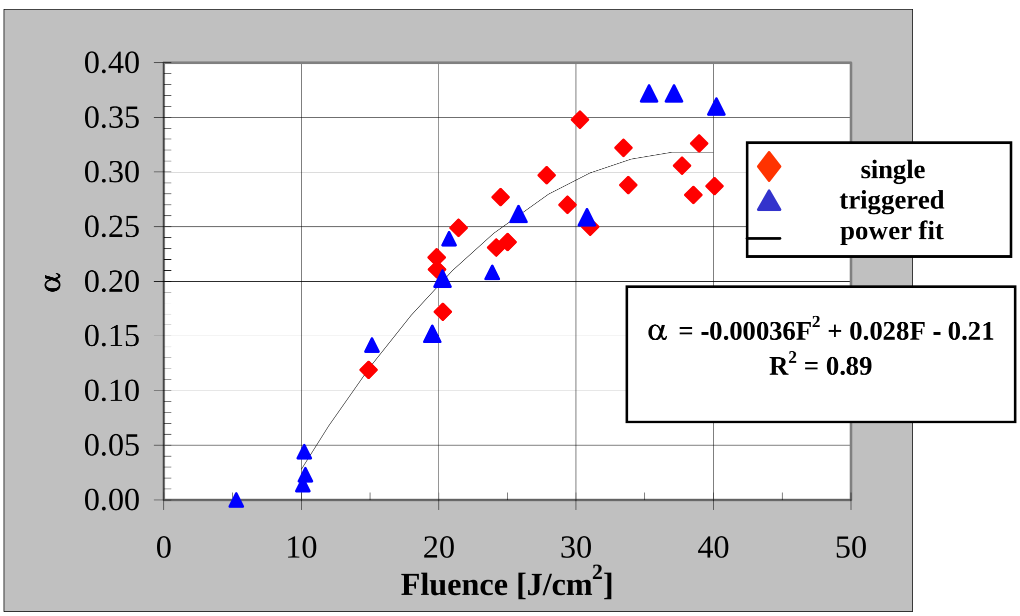


Figure 10. Triggered and single fluence growth data.

We note that the plot in figure 10 shows that the growth rates measured after a trigger shot are consistent with the data obtained at a single fixed fluence. In addition, as was found[2] at 527 nm, lowering the fluence to less than the single fixed fluence growth threshold of 15 J/cm^2 after a high fluence shot does not stop the growth. To entirely stop the growth the fluence had to be reduced to approximately 5 J/cm^2. Also included in figure 10 is power law fit to the data, which suggests that there may be a saturation effect as the fluence exceeds 30 J/cm^2.

3.4 Growth of input surface damage.

Previous work[2] at 527 nm reported a significant difference in the growth characteristics of laser damage when the damage is located on the input surface of the optic. In order to determine if this would also be the case at 1053 nm we placed one site which had been initiated on the exit surface on the input surface. This site was shot at 40 J/cm^2 and its growth data is plotted in figure 11; also, for comparison a site shot on the exit surface at the same fluence is shown.

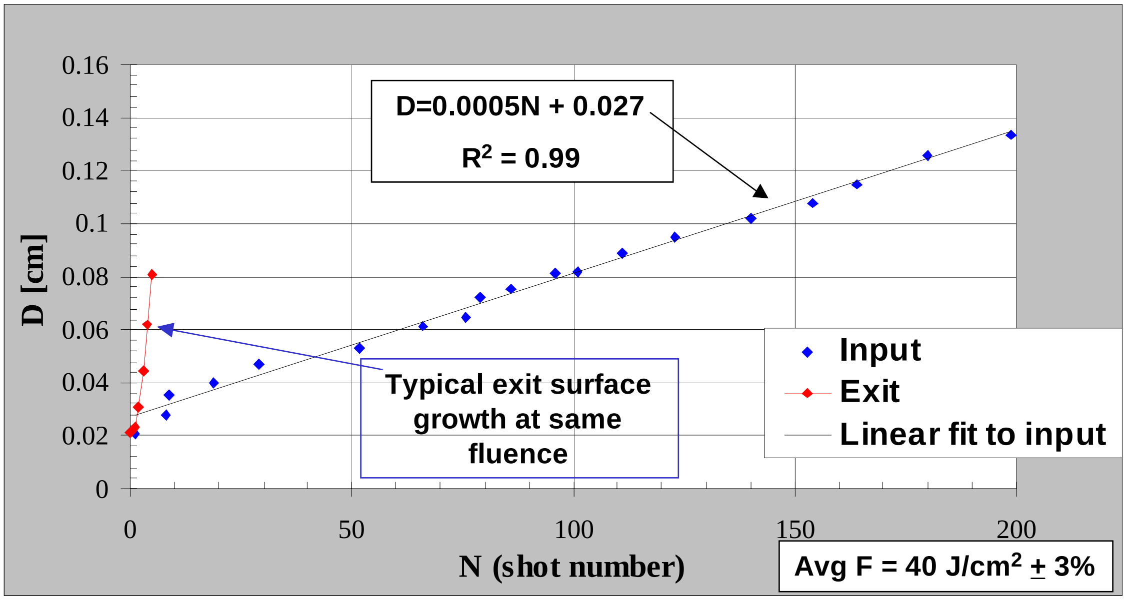
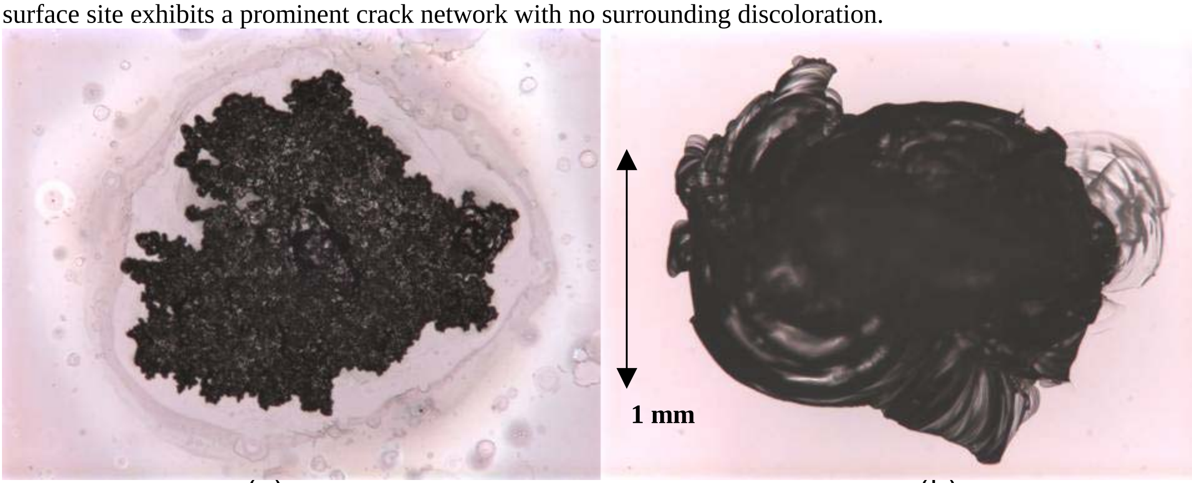


Figure 11. Growth of site located on input surface compared to exit surface site.

Over this growth sequence of two hundred shots, where the diameter increased seven-fold, the data is best fit to a linear function of shot number. This growth is not similar to that observed for damage located on the exit surface. Had this same site been positioned on the exit surface, we would expect that only 5 shots would have been required to grow the site to an 800 μm diameter whereas on the input surface it required 100 shots. This limited data suggests that input surface damage has a higher threshold for growth and input sites grow linearly in diameter. Also of interest is the final morphology seen on the input surface vs. that typically seen on the exit surface; figure 12 shows final high resolution micrographs for this input surface site (a) and an exit surface site (b) for comparison. The input surface site is very shallow, about 60 μm deep, and 1.5 mm in diameter. The exit surface site is deep, about 500 μm, and about 1.5 mm in diameter. The input site is very granular in appearance and is surrounded by a region looking like scald marks. The exit surface site exhibits a prominent crack network with no surrounding discoloration.



(a) (b)

Figure 12. Final images of sites grown at 1053 nm.

4. DISCUSSION

The measurements reported in this paper provide a database that can be used to predict the useful lifetime of a fused silica optic once one or more damage sites are initiated during 1ω operation. Exponential growth occurs when the damage is located on the exit surface. The experimental threshold for growth of 15 J/cm^2 implies that for operations always kept below this fluence one can expect that growth of laser damage sites will not limit the lifetime of the optic; many hundreds of shots should be possible before seeing any growth. Our tests showed no growth for as many as 300 shots. Above the experimental growth threshold, we have found that the magnitude of the exponential growth coefficient increases linearly with fluence.

We looked at the initial damage morphology as an aid in predicting whether a site will grow. Both the overall starting size and the individual pit size was found to be an indicator in predicting the potential for growth. The data obtained from sites shot with fluence ramped from low to high suggest that laser conditioning may help to increase the threshold for growth. The data obtained from sites triggered to grow at high fluence suggests that growth can occur for fluences less than the observed threshold of 15 J/cm^2; and that the fluence needs to be reduced to about 5 J/cm^2 to completely turn off growth once started.

If a site is located on the input surface, we found a linear dependence of the growth on shot number and a significant difference in the final morphology of the site grown on the input surface compared to sites grown on the exit surface. We believe that these different growth behaviors can be understood by recognizing that the deposition of the laser energy inside vs. outside the optic leads to differing plasma characteristics. With the site on the input surface, the plasma forms outside the optic and thus protects the surface. The damage is then shallow. The plasma is very hot; heat leads to ejection of oxygen-depleted material, and growth is primarily via redeposition. In contrast, for sites located on the exit surface the plasma forms inside the optic and the plasma is not as hot. The damage is deeper and exhibits large cracks, which grow faster. Growth is primarily via fracture.

ACKNOWLEDGEMENTS

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